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Field, laboratory, and modeling investigation of the skin effect at wells with slotted casing, Boise Hydrogeophysical Research Site

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Abstract

Understanding and quantification of wellbore skin improves our ability to accurately measure or estimate hydrologic parameters with tests at wells such as pumping tests, flowmeter tests, and slug tests. This paper presents observations and results from a series of field, laboratory, and modeling tests which, together, explain the source of wellbore skin at wells at a research wellfield and which support estimation of skin thickness (d_s) and skin hydraulic conductivity (K_s). Positive wellbore skin effects were recognized at wells in the shallow, unconfined, coarse-grained fluvial aquifer at the Boise Hydrogeophysical Research Site (BHRS). Well development efforts at the BHRS removed residual drilling fines but only marginally reduced the skin effect. Likely causes for the remaining wellbore skin effect were examined; partial clogging of screen slots with sand is consistent with field observations and can account for the magnitude of wellbore skin effect observed. We then use the WTAQ code (Barlow and Moench, 1999) with a redefinition of the term for delayed observation well response to include skin effects at observation wells (in addition to pumping wells) in order to analyze aquifer tests at the BHRS for average K_s values at individual wells. Systematic differences in K_s values are recognized in results at pumping (K_{s_Q}) and observation (K_{s_obs}) wells: larger values are seen at observation wells (average $K_{s\_obs}=0.0023$ cm/s) than pumping wells. Two possible causes are recognized for the occurrence of higher K_s values at observation wells than pumping wells: (1) flow diversion between aquifer layers on approach to a pumping well with positive skin; and (2) larger portion of flow passing through lower-K zones in the heterogeneous aquifer near the pumping well than the observation wells due to strongly radially convergent flow near the pumping well. For the well-aquifer system at the BHRS, modeling analyses of drawdown vs time at observation wells provide better K_s estimates than those from pumping wells.

Keywords: Wellbore skin; Well hydraulics; Modeling; Pumping tests

1. Introduction

Wellbore skin is a general term for imperfect hydraulic connection between a wellbore and the well structure and/or formation immediately outside the borehole. The imperfect connection may be due

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to: drilling, construction, or other effects on the well structure; composition and structure of annular fill; and/or changes in the formation near the well during or following the drilling process. Wellbore skin acts as a filter in series between the borehole and the undisturbed formation. As such, wellbore skin causes either an additional resistance to flow (positive skin) if it has lower hydraulic conductivity (K) than the undisturbed formation (e.g. invasion of drilling mud into the formation; encrustation or sand-clogging of a well screen), or causes a lessened resistance to flow (negative skin) if it has higher K than the undisturbed formation (e.g. sand or gravel pack in annular space).

Depending on the contrast in K between wellbore skin and the formation, the presence of wellbore skin can influence the use of a well, and can cause drawdown measured in a pumping well to give misleading values of K. Examples include lost production or added cost for operation in order to overcome additional head loss to achieve a given flowrate. Understanding the causes and magnitude of wellbore skin permits evaluation of effects and consideration of options to mitigate or quantitatively account for effects. Also, inclusion of values for skin improves our ability to get accurate formation parameters from hydrologic well tests (van Everdingen, 1953; Ramey, 1970; Faust and Mercer, 1984; Moench, 1984; 1997; Dane and Molz, 1991; Molz et al., 1994; Butler, 1998; Young, 1998; Dinwiddie et al., 1999; Rovey and Niemann, 2001).

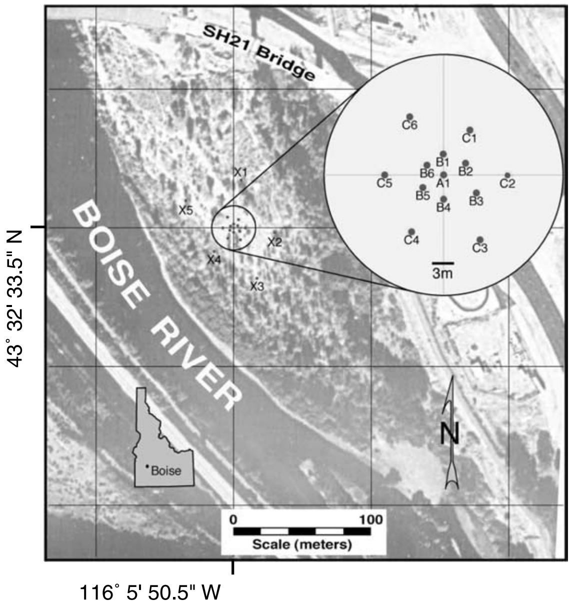

Fig. 1. Photomap showing the location and wellfield design of the Boise Hydrogeophysical Research Site (BHRS).

In this paper, we focus on the estimation of wellbore skin at the Boise Hydrogeophysical Research Site or BHRS (Fig. 1), a research wellfield that has been developed in a shallow, unconsolidated, coarse-grained fluvial aquifer (Barrash et al., 1999). Our interest in understanding and quantifying wellbore skin is to support subsequent investigations of heterogeneity of hydraulic parameters from hydrologic well tests at the BHRS. In this paper we: (a) describe the well construction method used at the BHRS and present evidence for positive wellbore skin; (b) examine causes for skin using field, laboratory, and modeling methods; (c) use our understanding of the cause for skin and a version of the WTAQ model (Barlow and Moench, 1999) that includes skin effects at observation wells, in addition to pumping wells, in order to analyze aquifer tests at the BHRS for skin hydraulic conductivity (K_s) values at individual wells; and (d) examine systematic differences in K_s values at pumping and observation wells and determine that these differences may be due to the conceptual model-error associated with (1) treating the aquifer as a homogeneous (one-layer) system rather than a multi-layered system, and perhaps also with (2) the 'pseudoskin' effect, or lower effective K in the immediate vicinity of a pumping well due to strongly convergent flow in a heterogeneous aquifer (Desbarats, 1992; Neuman and Orr, 1993; Rovey and Niemann, 2001).

2. Hydrogeologic setting and well construction

Field data for this paper are taken from the BHRS, which is located on a gravel bar adjacent to the Boise river 15 km east of downtown Boise, Idaho, USA. Eighteen wells were completed in the same manner (Fig. 2) within an 80 m×60 m area (Fig. 1). General stratigraphy at the site is: coarse-grained unconsolidated fluvial deposits underlain by clay (Barrash and Reboulet, 2004). Wells were designed to: (a) support a wide variety of hydrologic and geophysical testing; (b) provide hydraulic communication to the formation

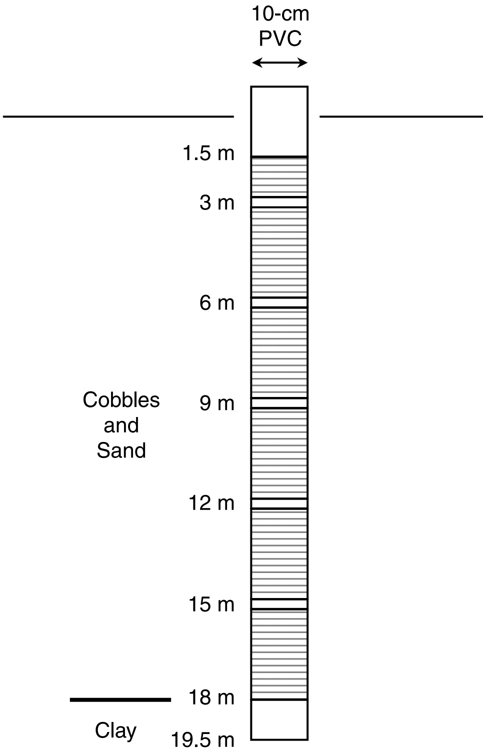

Fig. 2. Well construction and generalized stratigraphy at the BHRS.

throughout the saturated thickness of the unconfined fluvial aquifer; (c) maximize information gathered during the well construction process; and (d) minimize the volume of formation adjacent to the wells that may be disturbed by the drilling or installation processes (Barrash and Knoll, 1998).

Detailed information is provided here on well drilling, construction, and cleaning to support the understanding of wellbore skin at wells at the BHRS. Well materials that were used to meet the above-mentioned design criteria are (Fig. 2): 10 cm ID, 11.43 cm OD, schedule 40, PVC casing above the water table and below the fluvial aquifer; and 10 cm ID, 11.43 cm OD, schedule 40, PVC slotted casing (0.05 cm slot aperture) throughout the saturated thickness of the fluvial aquifer. The well construction and emplacement methods used were: (a) coring through the full thickness of the fluvial aquifer by driving a 0.6 m long, 6.03 cm diameter split spoon; (b) drilling with a 9.84 cm diameter bit following each 1.2 m of new coring; (c) using only synthetic (non-biodegradable) drilling mud; (d) driving 12.7 cm ID, 13.34 cm OD, steel casing with 15.24 cm OD drive shoe to new cored and drilled depths to hold back the formation—and also to hold back drilling cuttings from the borehole column prior to renewing coring; (e) drilling 1.5–3 m into the clay layer underlying the fluvial aquifer; (f) flushing the column with clean water; (g) setting the PVC screen and casing; and (h) pulling out the steel drive casing to allow collapse of the formation against the PVC screen and casing. Largely similar drilling and construction methods used by Morin et al. (1988) in sandy unconsolidated sediments and by Rehfeldt et al. (1989) in unconsolidated sand and gravel sediments were shown to produce a smaller radius of disturbance than wells that were augered or drilled with conventional mud (e.g. bentonite) and that were then stabilized with filter packs after drilling.

Initial well development following well installation was minimal. Approximately 0.47 L of common bleach (active ingredient: Na-hypochlorite) was added to each well to decompose the synthetic drilling mud to dissolved components. A surge block was moved down the well very slowly to distribute the bleach through and immediately outside the full length of saturated screened interval. Also, sand that had entered each well upon removal of the drive casing was pumped from the bottom of each well.

3. Evidence of wellbore skin

Positive wellbore skin causes excess drawdown in a pumped well compared to predicted drawdown based on hydraulic parameters determined from observation wells. Such wellbore skin effects were recognized in results from a fully penetrating pumping test conducted at the BHRS in 1998 with multiple fully penetrating observation wells (Fig. 3). For this test, well A1 was pumped at 171 L/min and drawdown was recorded in wells at radial distances of 3.6–40.1 m from A1. Type-curve matches to drawdown behavior at observation wells yielded similar aquifer parameters from analyses treating the aquifer as unconfined, homogeneous, and anisotropic (Table 1) using the WTAQ analytical model (Barlow and Moench, 1999). However, attempts to match the drawdown behavior of the pumping well with aquifer

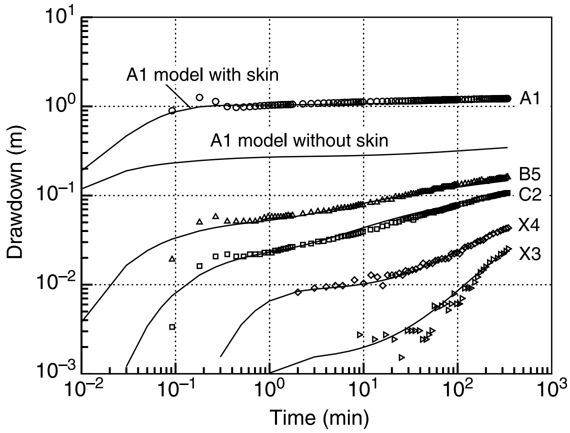

Fig. 3. Evidence of wellbore skin effect from a fully penetrating pumping test at the BHRS on October 22, 1998. Symbols are measured drawdowns; lines are model curves (see Table 1). Curve matches at observation wells have similar aquifer parameters, but use of these parameters for pumping well (A1) results in a type curve with considerably less drawdown than was observed. Observed drawdown at A1 can be matched with aquifer parameters determined at observation wells if wellbore skin and turbulent well losses are included at A1.

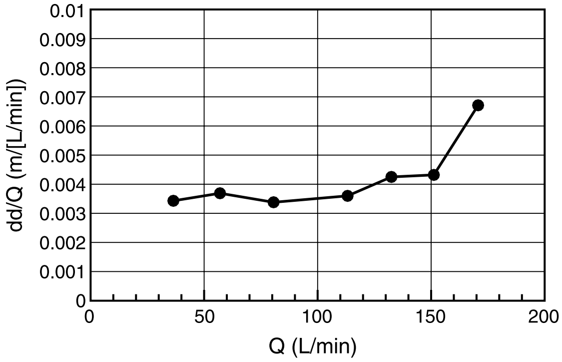

Fig. 4. Step test results from individual pumping tests at well A1. Drawdown per pumping rate is constant (i.e. no indication of non-linear well losses) to 114 L/min and then increases with increasing pumping rate.

parameters similar to those determined for the observation wells were not successful. In particular, drawdown in the pumping well (A1, see Fig. 1) was ~0.6 m greater than expected (Fig. 3).

Here we note that approximately half of the excess drawdown from the 1998 test may be attributed to turbulent well loss leaving about 0.3 m of excess drawdown that was not due to either formation (i.e. hydraulic head) loss or turbulent well loss. Fig. 4 shows step drawdown results for well A1 at the BHRS for seven pumping rates between 38 and 170 L/min. Each pumping test was conducted as a separate test. Drawdowns are compared at the same elapsed time of pumping (20.5 min). It is evident that: (a) drawdown per unit pumping rate is constant (within the noise of the experiments) at ~0.0035 m/(L/min) to at least 114 L/min; (b) additional drawdown per unit pumping rate (which may be attributed to non-linear well losses associated with entrance to the wellbore) occurs at pumping rates ≥132 L/min; and (c) drawdown at 170 L/min (or the pumping rate of the 1998 test—see Fig. 3) is approximately double (i.e. 0.6 m) what is expected without turbulent entry losses (i.e. 0.3 m). This excess drawdown of ~0.3 m was attributed to positive wellbore skin effects because well cleaning efforts prior to the 1998 test were minimal and because it is unlikely that one well surrounded by others with similar stratigraphy and lithology in a small area of the same aquifer (Barrash and Clemo, 2002; Barrash and Reboulet, 2004) would have significantly lower *K* (i.e. causing twice the expected drawdown) than the surrounding wells.

Table 1
Aquifer test data and results from curve-matching using the WTAQ code (Barlow and Moench, 1999) with pumping at 171 L/min from well A1 (prior to well cleaning) on October 22, 1998 and with aquifer thickness of 15 m (also see Figs. 1–3)

Well	*r* (m) from A1	K_r (cm/s)	K_z (cm/s)	S_s (m^{-1})	*Sy*[a]
B5	3.61	0.07	0.035	0.0001	0.03
C2	8.17	0.08	0.05	0.0001	0.03
X4	22.1	0.06	0.025	0.00013	0.15
X3	30.03	0.075	0.03	0.00013	0.12

Parameters defined in text.
[a] Anomalously low *Sy* values from analytical modeling of aquifer tests have been reported by numerous workers (e.g. Neuman, 1975; Moench, 1994; Chen and Ayers, 1998).

4. Possible causes for wellbore skin in wells at the BHRS

Given the positive skin effect observed in pumping test results, we examine possible causes for skin with the expectation that an understanding of the cause could provide options for removal, mitigation, and/or quantification of skin dimensions and magnitude. In this section, we consider the following possible causes: (1) compaction of the formation during the drilling and well construction processes; (2) invasion of the formation adjacent to the wells with residual synthetic drilling mud and fine cuttings from the drilling process; (3) head loss due to the well screen and blockage of entrances at the margin of the well screen; and (4) head loss due to partial sand-clogging of the well screen itself.

4.1. Possible compaction of the formation during well drilling and construction

As noted above in Section 2, the formation was held behind 13.34 cm OD drive casing during the drilling process. The question may arise as to whether the formation was compacted in the process and did not collapse against the slotted casing during well construction. In such a scenario, compacted material might cause or contribute to a positive skin effect. However, there are several reasons why compacted formation without collapse probably did not occur much at the BHRS wells. As noted above, a 15.24 cm OD drive shoe was welded to the bottom of the drive casing and we observed that sand invaded the screen of each well with removal of the drive casing indicating collapse against the screen for each well upon withdrawal of the drive casing. The drive casing was not removed easily and the considerable jerking and vibration during drive casing removal with the oversize drive shoe undoubtedly contributed to formation collapse as well. Also, geophysical testing for vertical seismic profiles of each well using a geophone pressed against the inner borehole wall with a bowspring indicated good mechanical coupling to the formation through the well screen (Michaels, 1998; 2001) and generated complete profiles without intervals of ringing or highly attenuated and noisy signals that would indicate zones of poor collapse (Dr P. Michaels, 2001, personal commun.). Also, the vast majority of the aquifer is cobbles and sand (Barrash and Reboulet, 2004) with framework cobbles which are not likely to compact and cause significant decrease in K in the same sense as more 'pliable' sands or finer-grained sediments might. Undoubtedly there are local places with incomplete collapse but these are not the norm or pervasive.

4.2. Possible invasion of the formation with drilling residues

Although care was taken in the drilling process to minimize escape of drilling mud and fine cuttings into the formation adjacent to the well (see Section 2 above), such invasion could occur to some degree during drilling between advancements of the drive casing. Also, initial efforts to remove residual drilling mud after well construction were not aggressive and likely influenced only a small radial distance outside a given well. Aggressive well development with surging has been recommended following well construction with the drive-and-wash method used here (Rehfeldt et al., 1989; Molz et al., 1994; Young, 1998), but we wanted to minimize rearrangement of grains in the formation to the extent possible. However, once skin was recognized, a series of additions of bleach and energetic surging were conducted at well C2 at the BHRS to determine if skin effects could be reduced and possibly removed in this manner. In this process, each addition and surging cycle was followed by a pumping test at C2 conducted at a similar pumping rate and with the same observation wells. Resulting skin effects were compared with those from a pre-treatment pumping test conducted for base performance characteristics prior to well development. The skin effect as measured by the dimensionless skin parameter of Moench (1997) is:

$$F_s = \frac{K_r * d_s}{r_w * K_s} \quad (1)$$

where K_s is skin hydraulic conductivity, d_s is skin thickness, K_r is radial hydraulic conductivity of the aquifer, and r_w is the radius of the pumping well at the screen. In this manner, a series of three aggressive surging treatments throughout the full-screened section of well C2 were conducted. The skin effect

Table 2
Predicted drawdown with fracture model for screen slot K, and observed drawdown in laboratory experiments

Pumping rate (L/min)/m of screen	Fracture model predicted drawdown (m)	Experimentally observed drawdown (m)
12.4	0.00021	–
37	0.00061	0.00067
74.5	0.00122	0.00168
112	0.00171	–
149	0.00247	0.00213
199	0.00335	0.00396
248	0.00396	0.00594
298	0.00488	0.00655

was reduced ∼30% by the first two treatments, but was not reduced further with a third treatment.

Considering the significant amount of remaining skin effect and the potential for affecting the porosity and permeability structure in the formation outside the wells with repeated aggressive surging, other wells were treated only with slow surging sufficient to mobilize residual fine cuttings. This process was monitored by observing dark material (mobilized fines) passing to the pump through the partially translucent intake hose. Slow surging was continued at each successive 1.5 m depth interval until the discharge clarified—usually requiring only a few minutes of surging per interval. Post-surging pumping tests showed only small reductions in drawdown or skin magnitude. With the removal of residual fines accomplished by slow surging but still having significant skin effect, we concluded that the remaining skin effect is largely due to causes other than drilling residues left in the formation. That is, we now focus our investigation on the well screen to examine head loss and quantify wellbore skin. In this regard, we take the radial thickness or radial width of the skin zone, d_s, to be equal to the wall thickness of the well screen, 0.635 cm.

4.3. Possible head loss due to screen or to blockage of screen entrance

Reconnaissance laboratory experiments were conducted to measure head loss associated with flow through the well screen (alone and with partial blockage of the entrance to the well screen) to determine if flow resistance at the well screen could account for the magnitude of additional drawdown caused by the skin effect at wells at the BHRS (e.g. ∼0.06–0.4 m additional drawdown at pumping rates of ∼62–114 L/min over ∼15 m of saturated screened interval). For these experiments, screen sections were placed in constant head water reservoirs while pumping, successively, at a series of constant rates inside the screen to determine head loss across the screen. Results (Table 2) indicate that head loss due to the screen alone is several orders of magnitude less than was observed in the field (e.g. Fig. 3) for pumping rates comparable to, or considerably greater than, those used in the field. For perspective on these results, we can calculate expected head loss across the screen using a fracture-flow conceptual model for the well screen.

Slotted PVC casing used in wells at the BHRS (Fig. 5A) has sets of factory-milled horizontal grooves with 0.05 cm aperture, which is the upper diameter of medium sand (Pettyjohn et al., 1973). Each groove is offset vertically from the next by 0.318 cm of blank casing. For a given 3 m section of slotted casing, ∼0.15 m is left blank at either end to provide mechanical strength where sections are screwed together (Figs. 2 and 5A). Also, horizontal grooves are interrupted by six vertical segments of blank casing at 60° radial intervals for mechanical strength such that ∼72% of the screen circumference is slotted and ∼28% is blank.

Overall, this geometry results in <10% porosity for the slotted sections; this porosity is less than the range of ∼12–50% porosity in the fluvial sediments at the BHRS (Barrash and Clemo, 2002). However, with respect to hydraulic behavior, slotted casing is more like a fractured medium than a porous medium. Using the slot aperture and spacing geometry given above, and calculating K for each screen slot as if it were a fracture between two smooth parallel plates

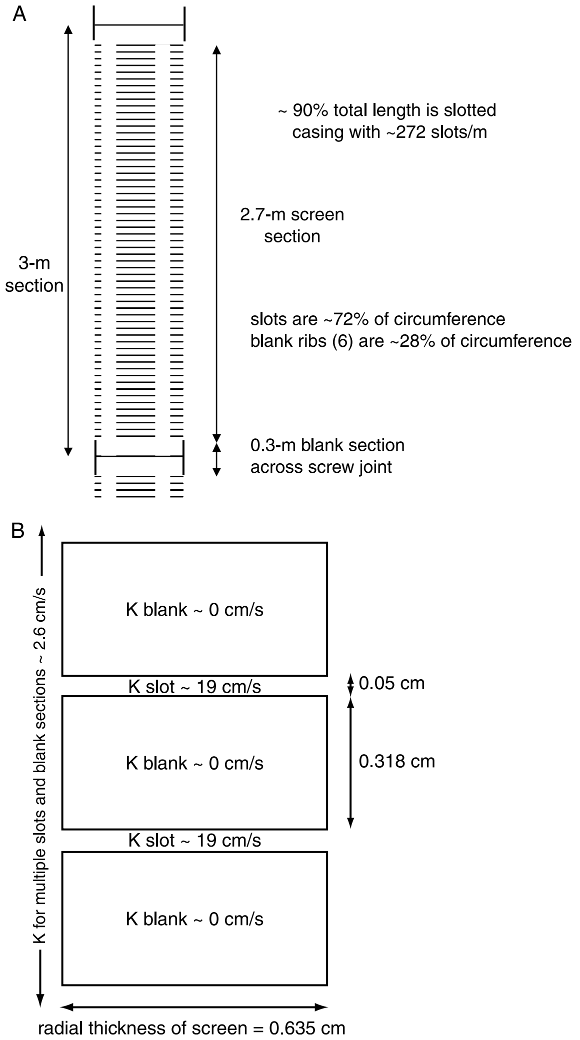

Fig. 5. (A) Schematic diagram of a typical 3 m section of 10 cm ID, schedule 40, slotted PVC casing with blank couplings at screw joints to adjacent screen sections. (B) Schematic cross-section of wall of PVC well screen with 0.05 cm slot apertures as parallel plate fracture sets.

(e.g. Witherspoon et al., 1980) then:

$$K_{\text{slot}} = \frac{b^2 \rho g}{12\mu} \cong 19 \text{ cm/s} \qquad (2)$$

for an individual fracture where b is the fracture or slot aperture, ρ is water density, g is gravity, μ is dynamic viscosity, and water is at 15.5 °C. Upscaled K for a set of such fractures (e.g. Snow, 1968; Moench, 1984), with each separated by 0.318 cm of impermeable blank PVC casing from the next fracture above or below, is 2.6 cm/s (Fig. 5B). Then, accounting for 28% of the screen circumference in blank casing, upscaled screen K becomes 1.87 cm/s.

Knowing the inside and outside diameters of the slotted casing (r=5.08 cm and R=5.72 cm, respectively), the pumping rate (Q) per length of screen (Δz), and upscaled K for the screen, and then imposing a constant head (H) boundary outside the screen, we can use the Theim equation:

$$h(r) - H(R) = \frac{Q}{2\pi K \Delta z} \ln \frac{r}{R} \qquad (3)$$

(e.g. deMarsily, 1986) to estimate drawdown due to the screen alone (Table 2). Results predicted by the slot fracture conceptual model are similar to those measured in the laboratory cell, with departures from the model (i.e. higher measured head loss) occurring at flow rates >200–250 (L/min)/m of screen (Table 2). Here we note that Eq. (3) does not account for non-linear head losses at the higher pumping rates.

To examine (on an order-of-magnitude basis) whether partial blockage of flow at the entrance to the screen would significantly increase head loss to magnitudes similar to those observed in the field, laboratory pumping tests were conducted with 40 and 60% of the open slot circumference blocked by strips of tape, and also by an undetermined percentage of blockage due to grains of fine gravel (average diameter ~4 mm) glued against the blank casing and positioned such that they were in contact with each other and centered across the slots. These tests were run at pumping rates between 37 and 298 (L/min)/m of screen. For comparison, total pumping rates of ~62–171 L/min during field tests at the BHRS are equivalent to ~4.1–11.4 (L/min)/m of screen length for ~15 m of screened saturated thickness. Results from these experiments (Fig. 6) indicate that: (a) aggregate screen K may be approximated as a medium with a regular fracture-set geometry; (b) K of slotted casing is approximately 1.9 cm/s, which is higher than K of any units in the unconsolidated fluvial deposits at the BHRS; and (c) partial blockage of the outer edge of the screen is an insufficient cause for the ~0.06–0.4 m of excess drawdown attributable to wellbore skin at the BHRS.

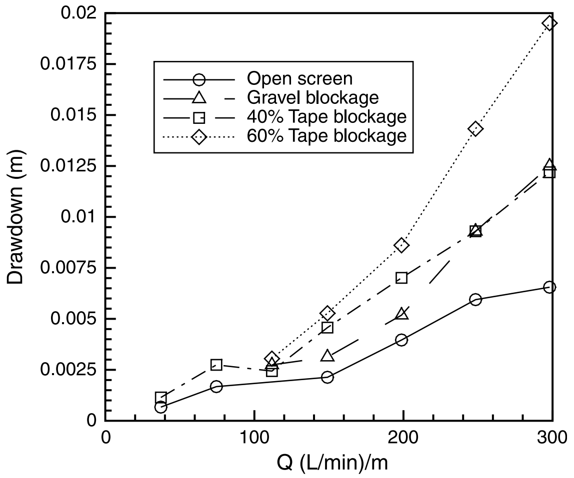

Fig. 6. Results of laboratory pumping tests of drawdown vs pumping rate per meter of screen. For reference, the range of pumping rates per meter of screen for BHRS pumping tests is 4.1–11.2 L/min/m, or less than any of the rates used in the laboratory pumping tests.

4.4. Possible head loss due to sand within screen slots

The remaining plausible cause for the wellbore skin effect in wells at the BHRS is partial clogging of screen slots due to invasion of sand grains. With the slot aperture the same dimension as the upper diameter of medium sand, invasion to some degree is likely to occur in the absence of a graded filter pack outside the well. Grain-size analyses of core from wells at the BHRS include fine to medium sand as part of the textural composition throughout the fluvial section (Reboulet, 2003). As noted above (Section 2), we know that sand passed into each of the wells at the BHRS during installation (i.e. with collapse of the formation against the screen during removal of the drive casing). It is reasonable to suppose that some sand grains remain in screen slots because they are wedged there or are resting in storage between transport events. And indeed some sand grains have been observed at the inner margin of slots in video logs of wells at the BHRS. In this section, we use numerical modeling experiments to examine if head losses associated with partial clogging of screen slots with sand might cause the magnitude of additional head loss observed during pumping tests at the BHRS.

4.4.1. Numerical modeling of head loss through partially clogged screen slots

To evaluate head loss through the screen due to reduced K per screen slot caused by partial clogging, an axisymmetric layered model was constructed using a modified version of MODFLOW-2000 (McDonald et al., 1988; Harbaugh et al., 2000) with: (a) a segment of slotted casing having the same radial and vertical geometry as slotted casing used in wells at the BHRS; (b) partially sand-clogged slots treated as granular aquifers that are separated from each other by blank screen sections treated as aquicludes (Fig. 7A); (c) a very high-K reservoir region outside the well screen that is bounded with constant head nodes; and (d) explicit treatment of the wellbore with very high K. Such explicit treatment in MODFLOW of a well with lateral variations of K in a layered axisymmetric system (Clemo, 2002) was developed to examine skin effects on well and near-well hydraulics (Clemo and Barrash, 2003).

Model results are given in Fig. 7B for drawdown on passage through partially sand-clogged screens having individual slot K values ranging from 0.14 to 0.0014 cm/s (average screen K of 0.019–0.00019 cm/s, respectively), and having equivalent pumping rates for fully penetrating pumping tests that range from 38 to 189 L/min at BHRS wells. To get head losses of approximately 0.3 m at 114 L/min, K values for individual partially sand-filled screen slots treated as aquifers are $\sim$0.005 cm/s per slot (Fig. 7). This K value for individual partially sand-filled screen slots is in the middle of the range of values for aquifers consisting of clean sand (e.g. Freeze and Cherry, 1979), or in the mid-to-upper part of the range for medium sand (e.g. Domenico and Schwartz, 1998). The equivalent average K value for the screen is $\sim$0.0007 cm/s. It appears then that partial sand-clogging of screen slots provides a plausible mechanism to cause, excess head loss of the magnitude observed in fully penetrating pumping tests at the BHRS.

5. Evaluation of skin with analytical modeling of aquifer tests

We can now evaluate average K_s values per well using analytical modeling to match results from fully

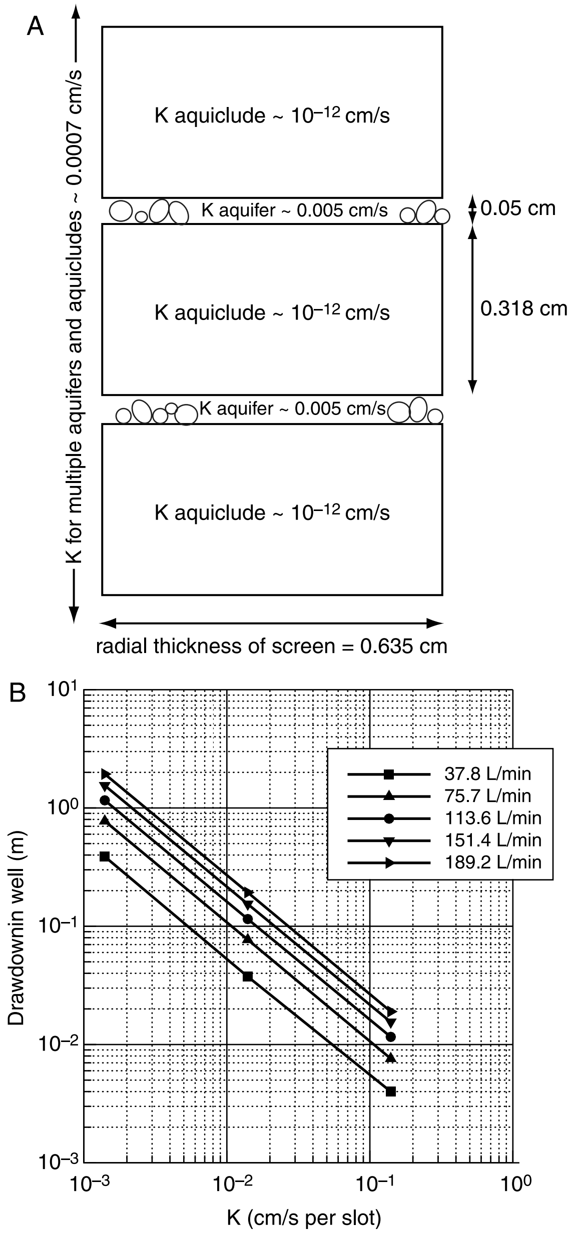

Fig. 7. (A) Schematic cross-section of wall of PVC well screen with sand invasion into 0.05 cm slot apertures treated as repeated layers of aquifers and aquicludes. (B) Drawdown vs K per individual screen slot (i.e. each partially sand-clogged slot treated as an aquifer in the model) at pumping rates scaled to be equivalent to rates in fully screened wells with 15 m of saturated thickness (i.e. as at the BHRS).

penetrating pumping tests. Because there are a number of closely spaced wells that are used alternately as pumping and observation wells, we include effects of wellbore skin at observation wells in the WTAQ code (Barlow and Moench, 1999) so we can then examine the consistency of wellbore skin results for a given well from a number of tests. Given that systematic differences between K_s at pumping wells (K_{s_Q}) and at observation wells (K_{s_obs}) result from this analytical modeling, we next consider two possible causes for additional head losses at pumping wells vs observation wells: (1) vertical flow divergence due to positive skin in a layered system and (2) strongly radially convergent flow effects in a heterogeneous system. We use modeling to show that the magnitude of the effect of vertical flow divergence is similar to (but in some cases perhaps less than) the difference between K_{s_Q} and K_{s_obs}. For this modeling, only results from aquifer tests at the BHRS with pumping rates ≤ 114 L/min are analyzed because these tests include formation and wellbore skin effects but likely do not include additional nonlinear head losses (Fig. 4). The effect due to radially convergent flow is considered below but the magnitude is difficult to evaluate without detailed knowledge of the heterogeneous K structure in the region affected by the pumping test.

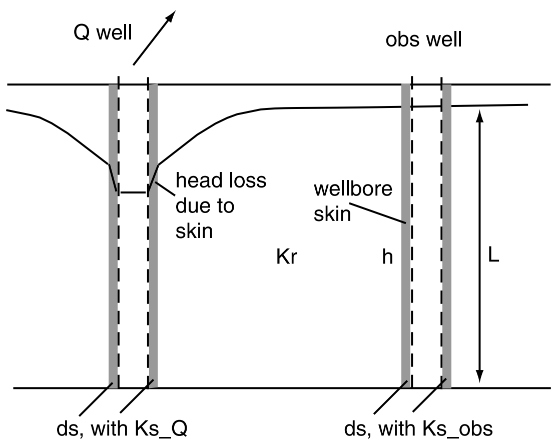

Fig. 8. Schematic diagram of pumping and observation wells with positive wellbore skin. L is screen length; K_s is hydraulic conductivity of the wellbore skin; d_s is radial thickness of wellbore skin; K_r is aquifer hydraulic conductivity; and h is head in the aquifer immediately adjacent to the wellbore skin. See Eq. (4) for statement of flow balance at the observation well. Not to scale.

5.1. Analytical model with observation well skin

The WTAQ analytical modeling code (Barlow and Moench, 1999) includes the capability to simulate wellbore skin effects at a pumping well. Here we include the capability to also simulate wellbore skin effects at observation wells as an independent check because we model drawdown behavior at a number of wells which are alternately used for pumping and observation.

The basis for analyzing wellbore skin at an observation well may be stated mathematically in terms of the head and flow balances that must occur at the interface between the aquifer and the skin that surrounds the well (Fig. 8):

$$\pi r_{\mathrm{obs}}^2 \frac{\partial h_{\mathrm{obs}}}{\partial t} = 2\pi r_{\mathrm{obs}} L K_{\mathrm{s}} \frac{(h - h_{\mathrm{obs}})}{d_{\mathrm{s}}} \quad (4)$$

where r_{obs} is the radius of the observation well; h_{obs} is measured head in the observation well; h is head in the aquifer; and L is the length of open screen. This condition may be included as a redefinition of the term for delayed observation well response in the existing WTAQ formulation (Barlow and Moench, 1999) which is solved with dimensionless parameters in the Laplace domain (see Appendix A) and then numerically inverted with the Stehfest (1970) algorithm.

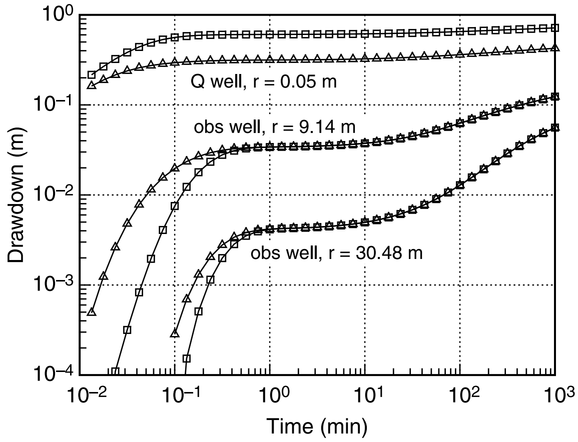

Fig. 9. Log–log drawdown vs time plots comparing the effects of no wellbore skin ($F_s = 0$, curves with triangle symbols) with positive wellbore skin ($F_s = 5$, curves with square symbols) at pumping and observation wells for a system similar to that at the BHRS. At a pumping well, skin causes increased drawdown. At observation wells, skin causes delay in drawdown equilibration between the well and the aquifer (most pronounced in early time).

Wellbore skin effects on drawdown behavior are different at pumping and observation wells (e.g. Fig. 9, see also Fig. 7 in Moench, 1985). For positive skin, additional drawdown occurs at the pumping well to drive the required flowrate through the skin or low-K filter zone between the aquifer and the well. This effect occurs throughout the pumping period. At the observation well, the low-K filter zone causes a delay in the equilibration of head between the observation well and the surrounding aquifer. This effect is most pronounced at the early time of observation well response, especially as seen in log-log plots of drawdown vs time (Fig. 9).

5.2. Results at pumping and observation wells

WTAQ was used to determine K_s and aquifer parameters from pumping tests run in 1999 at the BHRS after well cleaning was performed to remove residual synthetic drilling mud and drilling fines (see Section 2). K_s and aquifer parameter results from nine tests run at ≤ 114 L/min at A, B, and C wells in the central portion of the BHRS (Fig. 1) are given in Table 3 (Fox, in prep.). For these analyses, curve matches were generated by forward modeling in a sequential process using known inputs for pumping rate and aquifer thickness while varying K, Ss, Sy, and wellbore skin by trial and error at a given pumping and observation well (i.e. one pair of wells at a time).

Initially estimates for K, Ss, and Sy came from analysis of aquifer tests at observation wells without consideration of skin at either the pumping well or observation wells (e.g. Fig. 3, Table 1). Then, a curve match was obtained at a given pumping well using WTAQ with the inclusion of the pumping well skin effect and starting values for K, Ss, and Sy from the initial curve-matching step. Next, curve matches were obtained with the inclusion of skin values at the observation well using K_{s_Q} from the previous step as the initial estimate for K_{s_obs}. It soon was recognized that highly variable and, commonly, unrealistically low Ss values were required to obtain matches at observation wells if K_{s_obs} values were forced to be the same as K_{s_Q} values from the previous step. However, Ss is not expected to vary widely or have unusual values in the small volume of coarse fluvial

Table 3
Screen K and aquifer parameter values from analytical modeling

Well	A1	B2	B3	B4	B5	B6	C3	C5	C6
Q (L/min)	113	85	113	112	110	111	62	110	87
n_Q[a]	5	5	5	5	5	4	3	5	5
Ave K_{s_Q} (cm/s)	9.5×10^{-4}	1.3×10^{-3}	2.55×10^{-3}	1.05×10^{-3}	8.5×10^{-4}	5.0×10^{-4}	1.3×10^{-3}	1.0×10^{-3}	5.5×10^{-4}
Min K_{s_Q} (cm/s)	9.0×10^{-4}	9.5×10^{-4}	2.1×10^{-3}	9.5×10^{-4}	8.0×10^{-4}	4.5×10^{-4}	1.2×10^{-3}	9.0×10^{-4}	5.0×10^{-4}
Max K_{s_Q} (cm/s)	1.0×10^{-3}	1.55×10^{-3}	3.1×10^{-3}	1.15×10^{-3}	9.0×10^{-4}	5.0×10^{-4}	1.45×10^{-3}	1.05×10^{-3}	6.0×10^{-4}
n_{obs}[b]	10	5	4	5	2	5	4	3	3
Ave K_{s_obs} (cm/s)	1.95×10^{-3}	2.5×10^{-3}	2.2×10^{-3}	2.3×10^{-3}	2.25×10^{-3}	2.55×10^{-3}	1.75×10^{-3}	2.1×10^{-3}	2.6×10^{-3}
Min K_{s_obs} (cm/s)	1.5×10^{-3}	1.85×10^{-3}	1.8×10^{-3}	2.0×10^{-3}	1.8×10^{-3}	2.0×10^{-3}	1.6×10^{-3}	1.5×10^{-3}	2.35×10^{-3}
Max K_{s_obs} (cm/s)	3.0×10^{-3}	3.1×10^{-3}	3.1×10^{-3}	2.7×10^{-3}	2.7×10^{-3}	2.7×10^{-3}	1.8×10^{-3}	3.1×10^{-3}	3.1×10^{-3}
Ave K_r (cm/s)	.085	.065	.085	.075	.080	.065	.11	.080	.065
Min K_r (cm/s)	.060	.050	.065	.065	.065	.050	.10	.050	.050
Max K_r (cm/s)	.10	.080	.10	.080	.10	.080	.13	.095	.075
Ave K_z[c] (cm/s)	.085	.055	.080	.075	.080	.060	.105	.065	.045
Min K_z (cm/s)	.060	.035	.065	.065	.065	.035	.13	.045	.025
Max K_z (cm/s)	.10	.080	.10	.080	.10	.080	.085	.095	.075
Ave Ss (m^{-1})	5.2×10^{-5}	4.3×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	4.6×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	3.9×10^{-5}
Min Ss (m^{-1})	3.3×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	3.3×10^{-5}
Max Ss (m^{-1})	1.3×10^{-4}	8.2×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	9.8×10^{-5}	3.3×10^{-5}	3.3×10^{-5}	4.9×10^{-5}
Ave Sy[d]	.030	.033	.020	.026	.022	.032	.031	.022	.034
Min Sy[d]	.013	.020	.015	.017	.015	.025	.017	.017	.030
Max Sy[d]	.060	.060	.025	.040	.030	.040	.060	.030	.040

[a] n_Q refers to the number of observation wells paired with a given pumping well from one pumping test.
[b] n_{obs} refers to the number of pairings of a given well as an observation well with different wells as pumping wells (i.e. during n_{obs} different pumping tests).
[c] Not all pumping-observation well pairs exhibited anisotropic behavior but, for simplicity here, average values include results from all well pairs.
[d] Anomalously low Sy values from analytical modeling of aquifer tests have been reported by numerous workers (e.g. Neuman, 1975; Moench, 1994; Chen and Ayers, 1998).

aquifer under study at the BHRS (Fig. 1). So, in the final step, curve matches are obtained for a given pumping well-observation well pair by (a) allowing K_{s_obs} to be greater than K_{s_Q} while (b) all other aquifer parameters are the same for the pumping and observation well (Table 3). A reasonable starting value for Ss in this last step is $3.3\times10^{-5}\ m^{-1}$, considering the discussion above as well as expected values for Ss in this type of aquifer (e.g. Domenico and Schwartz, 1998, Table 4.1).

Several patterns are evident from the K_s results presented in Table 3: (a) in all but one case, K_s values at observation wells are higher than at pumping wells, and generally they are ~1.5–5 times higher; (b) K_{s_obs} values from matches at individual observation wells are similar (average $K_{s\_obs}=0.0023$ cm/s); and (c) K_{s_Q} values from matches at individual pumping wells have a wider range overall than for observation wells. Although the magnitudes of differences between and among K_s values for pumping or observation wells are not great overall, relatively small differences in K_s can result in significant differences in drawdown behavior (e.g. Fig. 7B).

5.3. Possible causes for higher K_s values at observation wells than pumping wells

We now consider why K_s values at observation wells are, with only one exception, greater than K_s at pumping wells from analytical modeling of field data at pumping well-observation well pairs. Such systematic differences may occur if drawdown at a pumping well includes other head loss effects beside formation and screen losses that are not active or not as pronounced at observation wells. Here we are excluding non-linear entrance losses because we are analyzing BHRS pumping tests run at ≤114 L/min (Table 3). Two possible causes are recognized for the occurrence of lower K_s values at pumping wells than observation wells: (1) flow diversion between aquifer layers on approach to a pumping well with a positive skin (Young, 1998; Halford, 2000; Clemo and Barrash, 2003); and (2) larger portion of flow passing through lower-K zones near the pumping well in a heterogeneous aquifer than at observation wells due to strongly radially convergent flow near the pumping well (Desbarats, 1992; Neuman and Orr, 1993; Rovey and Niemann, 2001). These two possible causes for lower K_s values at pumping wells are discussed below.

5.3.1. Possible additional head loss due to flow diversion in a layered system

Here it is important to note that the WTAQ model assumes a homogeneous (one-layer) aquifer system, but the aquifer at the BHRS is a four- or five-layer system (Barrash and Clemo, 2002; Barrash and Reboulet, 2004). Vertical flow diversion can occur between layers in the vicinity of a pumping well with positive skin in layered aquifer systems (Fig. 10) (Young, 1998; Halford, 2000; Clemo and Barrash, 2003). The positive skin zone decreases effective K_r near the well for all layers because the relatively lower K_s acts in series with the relatively higher K_r of either higher- or lower-K_r layers. In detail, the effective K_r values adjacent to the wellbore at relatively high-K_r layers are reduced more (due to harmonic averaging of K_s and high-K_r in series) than are effective K_r values at relatively lower-K_r formation layers. That is, a net effect of the positive skin zone (i.e. low-K filter in series with each aquifer layer) is to distort the near-wellbore head and flow profiles of the layers relative to the head and flow profiles of the layers at some radial distance from the wellbore where approximately horizontal radial flow occurs in all layers (Fig. 10B), and accordingly where head contours are approximately vertical (Javandel and Witherspoon, 1969; Molz et al., 1994). With or without skin, the wellbore is essentially a constant-head boundary and the constant pumping rate means the total flux of all layers is constant. Therefore, for wells with positive skin, some redistribution of flow between layers must occur in the near-wellbore region (i.e. in the region between the nearly vertical head contour at the wellbore and the vertical head contours at some radial distance from the wellbore, see Fig. 10B). That is, some flow is diverted from the higher-K_r layers to the lower-K_r layers and the near-wellbore flowfield now includes vertical components with corresponding additional head losses.

Vertical flow diversion, then, is a mechanism that: (a) is associated with positive wellbore skin and a layered aquifer system; (b) can cause head losses at a pumping well larger than predicted with a

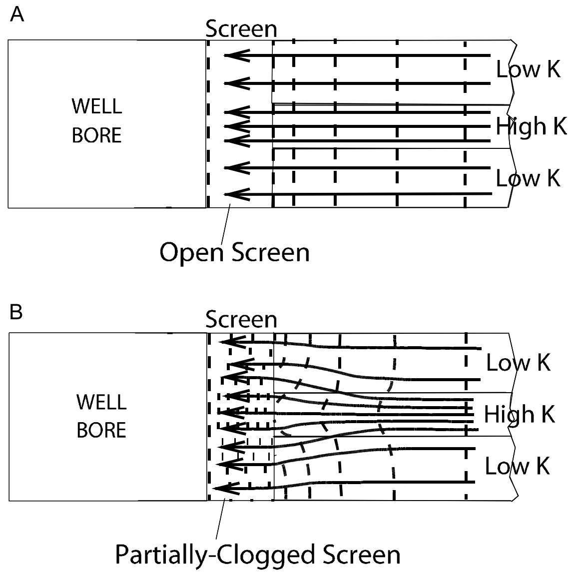

Fig. 10. Schematic diagram of flow to a well in a layered system. (A) Horizontal radial flow to well without wellbore skin. (B) Flow diversion from higher K layer to lower K layers on approach to well with positive wellbore skin. Due to the low value of K_s in the skin zone, effective K_r in the high-K layer in series with K_s (i.e. immediately adjacent to the well) is reduced more than in the low-K layers. This relatively greater reduction in effective K_r in the high-K layer results in relatively less flow passing through this layer and thus, relatively more flow passing through the lower-K layers above and below, which are less affected (in an effective K_r sense) by K_s of the skin zone.

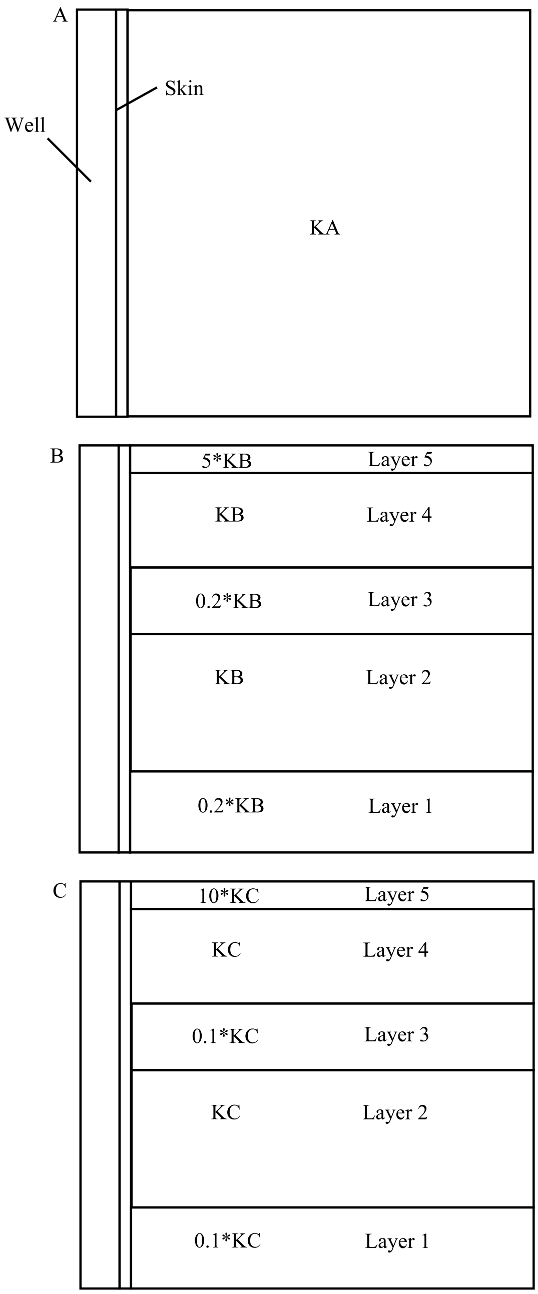

Fig. 11. Examining conceptual model-error due to layering and positive skin. Three layering scenarios, all with the same average K_r, are used in axisymmetric MODFLOW models with skin for comparison against drawdown observed at the pumping well: (A) one layer. (B) Five layers with ~1 order of magnitude range of K_r between layers. (C) Five layers with ~2 orders of magnitude range of K_r between layers.

homogeneous model; and (c) is not included in the WTAQ analytical model. To estimate the magnitude of such an effect for an aquifer system like that at the BHRS, a series of numerical modeling experiments were run (Fig. 11, Table 4) with: (a) a base case of a homogeneous (one-layer) aquifer; (b) a five-layer aquifer having about one-order of magnitude of range in K_r but the same average K_r as that of the one-layer aquifer base case; and (c) a five-layer aquifer having about two-orders of magnitude of range in K_r but the same average K_r as that of the one-layer aquifer base case. The general geometry and aquifer parameter values used for this modeling are similar to those at the BHRS.

As was the case for the numerical experiments on the partially sand-filled screen (see Section 4.4.1), we use the axisymmetric cylindrical geometry grid configuration in MODFLOW-2000 (Clemo, 2002; Clemo and Barrash, 2003). Test conditions include pumping at 112 L/min in a 15 m thick aquifer in order to compare results with six tests at the BHRS run at 112±2 L/min (Table 3). Three different average K_r values (Table 4) are considered to examine variation similar to what occurs at the BHRS (Fox, in prep.). Results indicate that the additional head loss due to vertical flow diversion between layers near the pumping well caused by positive skin in a 15 m thick, layered system with moderate K_r contrast is on the order of ~0.05–0.12 m (Table 4). If we subtract head loss of this magnitude (i.e. drawdown unaccounted for in WTAQ) from drawdown measured at pumping wells at the BHRS and use the average K_{s_obs} (0.0023 cm/s) to match drawdown curves with WTAQ (i.e. in a single-layer system with the same average K_r), then good matches can be obtained for most pumping tests without changing aquifer parameters determined in previous matches at the respective pumping well-observation well pair for most pumping tests (Table 5). For matching these curves, K_{s_Q} is about equal to K_{s_obs}.

We have similarly checked to see if the layering effect might cause time-delay differences from a one-layer (equivalent average K_r) aquifer at an observation well with wellbore skin. Some delay due to layering is recognizable at nearby observation wells for an ideal pumping system,

Table 4
Modeling data for investigating head loss due to layering and K_r range for a 15 m thick aquifer or aquifer system pumped at 112 L/min

K_{s_Q} (cm/s)	Average K_r (cm/s)	Number of aquifer layers	K_r range	Drawdown at pumping well (m)	Drawdown difference vs 1-layer model (m)
0.0023	0.06	1	1	0.479	–
0.0023	0.06	5	~10	0.533	0.054
0.0023	0.06	5	~100	0.600	0.122
0.0023	0.075	1	1	0.405	–
0.0023	0.075	5	~10	0.454	0.049
0.0023	0.075	5	~100	0.512	0.107
0.0023	0.09	1	1	0.354	–
0.0023	0.09	5	~10	0.399	0.045
0.0023	0.09	5	~100	0.454	0.100

but delays are minimal (and hence influences on skin estimates are minimal) for matches to real data where initial pumping rates are variable for the first few seconds before stabilizing.

5.3.2. Possible additional head loss due to radially convergent flow near the pumping well in a heterogeneous system

Desbarats (1992) and Neuman and Orr (1993) have shown that the effective or average K_r at a pumping well in a heterogeneous aquifer (such as that at the BHRS) may appear to be less than the effective or average K_r at an observation well. With the strongly radially convergent flow conditions at a pumping well, flow adjacent to the well must occur through all local low-K_r zones or lenses as well as high-K_r zones to reach the well. In contrast, at some radial distance away from the pumping well, where gradients are not strongly converging, flow passing in the vicinity of an observation well can preferentially follow higher-K_r flow paths (Desbarats, 1992). Rovey and Niemann (2001) note this difference in effective K_r (i.e. geometric mean K_r at observation well > harmonic mean K_r at pumping well) may result in misinterpretation of well tests and they use the term 'pseudoskin' for the lower K_r at pumping or slug wells vs observation wells. The pseudoskin effect may explain some additional K_{s_obs} vs K_{s_Q} differences beyond what are caused by layering, but current understanding of the three-dimensional K_r distribution at

Table 5
K_{s_Q} and K_{s_obs} values from an example set of pumping tests with drawdown at pumping wells adjusted for conceptual model-error due to layering

Q well	Obs well	r to obs well (m)	Q (L/min)	K_{s_Q} (cm/s)	K_{s_obs}[a] (cm/s)	K_r ave (cm/s)	Drawdown difference used for match at pumping well (m)
A1	B5	3.61	113	0.0023	0.00195	0.1	0.122
B4	B6	4.72	112	0.0023	0.0023	0.065	0.076
B5	B4	3.38	110	0.0023	0.0023	0.065	0.012
B6	B2	5.34	111	0.0023	0.00255	0.075	0.122[b]
C5	C6	8.58	110	0.0023	0.0021	0.075	0.091

[a] K_{s_obs} value is the same as was used in original curve match (Table 3).
[b] Adjustment of drawdown at the pumping well due to the layering effect moves data closer to the type curve with K_{s_Q} = 0.0023 cm/s, but significantly greater drawdown adjustment or reduced K_{s_Q} is necessary to obtain a match.

the BHRS is insufficient to quantitatively evaluate this effect.

6. Discussion

For aquifers with variation in K of $\sim$1–2 orders of magnitude in layered systems with positive wellbore skin at pumping wells, a potentially significant fraction of the drawdown at such a pumping well may be due to flow diversion between layers near the wellbore. Our analysis in Section 5 shows that the general magnitude of head loss associated with such flow diversion may be comparable to that occurring for a modest range of K in layered systems that are generally similar to the aquifer system at the BHRS (Tables 4 and 5). This allows, but does not require, that using an approximation of homogeneity (conceptual model-error) is a major cause of the drawdown difference. That is, we now have a rationale for applying fitting adjustments that are sufficient to achieve matches which give a reasonable K_{s_Q} result in most cases, but we do not know if other factors are involved and/or if the amount of drawdown adjustment used is correct.

To this point, we have not considered finer-scale heterogeneity although there is reason to believe that K varies within some layers, as well as between layers, at the BHRS (Barrash and Clemo, 2002; Goldstein et al., 2003; Barrash and Reboulet, 2004). Indeed, variation within layers is expected in natural, high-energy, coarse-grained fluvial deposits (Bluck, 1979; Steel and Thompson, 1983; Dawson and Bryant, 1987) and may also contribute to the 'pseudoskin' effect (i.e. additional cause of head loss and apparently lower K_{s_Q} values) associated with radially convergent flow near pumping wells.

In a somewhat similar manner, we assume a constant average K_s but it is likely that K_s will vary to some extent throughout a given well screen. As a first approximation, it is reasonable to assume (as we have done in this paper) that such variations are not great because the screen is everywhere adjacent to sediments with available sand of medium and finer grain sizes. However, we acknowledge that local variations of K_s could enhance or reduce head losses compared to those due to constant average K_s.

7. Summary and conclusions

Positive wellbore skin effects were observed in pumping test data from wells that were completed with 10 cm ID, schedule 40, PVC slotted casing in unconsolidated coarse-grained fluvial deposits using a drilling method where: the formation was held back by drive casing; synthetic mud was used; and the formation was allowed to collapse against the well screen upon removal of the drive casing. Residual synthetic drilling mud was decomposed with bleach and drilling fines were removed with surging and pumping, but these treatments did little to reduce the positive skin effect.

Laboratory tests and associated modeling experiments on screen alone and on screen with partial blockage of slots did not generate the magnitude of drawdown attributed to skin during pumping tests. However, numerical modeling experiments and associated field observations of partially sand-filled screen slots are consistent with additional drawdown attributed to skin effects seen in pumping tests at the BHRS in 1999. Step tests demonstrate that non-linear head losses at inflow to well A1 at the BHRS are not apparent at pumping rates $\leq$114 L/min and so, likely, do not contribute to drawdown measured in most of the 1999 pumping tests.

Analytical modeling of pumping tests at the BHRS after well cleaning (i.e. after dissolution of synthetic drilling mud and removal of residual fines outside the well screen) yields similar K_{s_obs} values (average $K_{s\_obs}=0.0023$ cm/s) for nine wells. Skin K values at these wells when they were used as observation wells are less variable and (with one exception) are higher by $\sim$1.5–5 times compared with K_s at the same wells when they were used as pumping wells. After accounting for conceptual model-error due to treating the system as a homogeneous (one-layer) aquifer rather than as a multilayered aquifer, much or all of the difference may be removed between K_s determined at observation or pumping wells for most tests. Also, the pseudoskin effect due to strongly radially convergent flow at pumping wells in heterogeneous aquifers is another mechanism for additional head loss at pumping wells which, if present, would be incorporated into K_s by default. For the above reasons, modeling analyses of drawdown vs time at observation wells provide better K_s estimates than those from pumping wells in the well-aquifer system at the BHRS.

Acknowledgements

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Appendix A. Laplace transform solution for delayed observation well response including skin effect at the observation well

Here we present the basis for including wellbore skin effects at an observation well in the context of the analytical solution for well and aquifer hydraulics for an axisymmetric, homogeneous system that can be unconfined or confined, isotropic or anisotropic, with pumping and observation wells that can be fully or partially penetrating, and can have finite or infinitesimal diameter (Moench, 1997; Barlow and Moench, 1999). We start with the expression for head and flow balance at the interface between the aquifer and the observation well screen.

$$\pi r_{\mathrm{obs}}^2 \frac{\partial h_{\mathrm{obs}}}{\partial t} = 2\pi r_{\mathrm{obs}} L \frac{K_{\mathrm{s}}}{d_{\mathrm{s}}}(h - h_{\mathrm{obs}}) \tag{A1}$$

Next we introduce dimensionless quantities for time and skin at the observation well and then for head in the aquifer and observation well.

$$t_{\mathrm{D}} = \frac{K_{\mathrm{r}} t}{r_{\mathrm{w}}^2 S_{\mathrm{s}}} \tag{A2}$$

$$F_{\mathrm{s\_obs}} = \frac{K_{\mathrm{r}} d_{\mathrm{s}}}{r_{\mathrm{obs}} K_{\mathrm{s}}} \tag{A3}$$

(Eq. (A1)) is revised to maintain a dimensionless system:

$$\frac{K_{\mathrm{r}} \pi r_{\mathrm{obs}}^2}{r_{\mathrm{w}}^2 S_{\mathrm{s}}} \frac{\partial h_{\mathrm{obs\ D}}}{\partial t_{\mathrm{D}}} = 2\pi L \frac{r_{\mathrm{obs}} K_{\mathrm{s}}}{d_{\mathrm{s}}}(h_{\mathrm{D}} - h_{\mathrm{obs\ D}}) \tag{A4}$$

where

$$h_{\mathrm{D}} = 4\pi K_{\mathrm{r}} b(h_0 - h)/Q \tag{A5}$$

and

$$h_{\mathrm{obs\ D}} = 4\pi K_{\mathrm{r}} b(h_0 - h_{\mathrm{obs}})/Q \tag{A6}$$

Rearranging (Eq. (A4)) gives

$$\frac{\pi r_{\mathrm{obs}}^2}{2\pi r_{\mathrm{w}}^2 S_{\mathrm{s}} L} \frac{\partial h_{\mathrm{obs\ D}}}{\partial t_{\mathrm{D}}} = \frac{r_{\mathrm{obs}} K_{\mathrm{s}}}{K_{\mathrm{r}} d_{\mathrm{s}}}(h_{\mathrm{D}} - h_{\mathrm{obs\ D}}) \tag{A7}$$

which may be restated as

$$W'_{\mathrm{D}} F_{\mathrm{s\_obs}} \frac{\partial h_{\mathrm{obs\ D}}}{\partial t_{\mathrm{D}}} = h_{\mathrm{D}} - h_{\mathrm{obs\ D}} \tag{A8}$$

where

$$W'_{\mathrm{D}} = \frac{\pi r_{\mathrm{obs}}^2}{2\pi r_{\mathrm{w}}^2 S_{\mathrm{s}} L} \tag{A9}$$

or as

$$W''_{\mathrm{D}} \frac{\partial h_{\mathrm{obs\ D}}}{\partial t_{\mathrm{D}}} = h_{\mathrm{D}} - h_{\mathrm{obs\ D}} \tag{A10}$$

where

$$W''_{\mathrm{D}} = W'_{\mathrm{D}} F_{\mathrm{s\_obs}} \tag{A11}$$

(Eq. (A11)) leads to

$$p W''_{\mathrm{D}} \bar{h}_{\mathrm{obs\ D}} = \bar{h}_{\mathrm{D}} - \bar{h}_{\mathrm{obs\ D}} \tag{A12}$$

where p is the Laplace transform variable. And thus, it follows that dimensionless head at the observation well in the Laplace domain is

$$\bar{h}_{\mathrm{obs\ D}} = \frac{\bar{h}_{\mathrm{D}}}{1 + p W''_{\mathrm{D}}} \tag{A13}$$

which is of the same form as Eq. (30) of Moench (1997) for dimensionless head in the Laplace domain at the pumping well.

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